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Sustainable Synthetic Fuels

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The extensive use of fossil hydrocarbons and their derived products in the energy, transport and petrochemical sectors is a major source of greenhouse gas (GHG) emissions and ties our society to ever dwindling reserves. In this context, synthetic fuels represent alternative energy carriers (and in some cases raw materials) that could be easily integrated into existing systems. Based on "Power-to-Gas (PtG)" and "Power-to-Liquid (PtL)" schemes that convert intermittent green power to chemical energy, these synthetic fuels could play a crucial role in establishing carbon neutral energy provision, importantly based on CO_2 recycling.

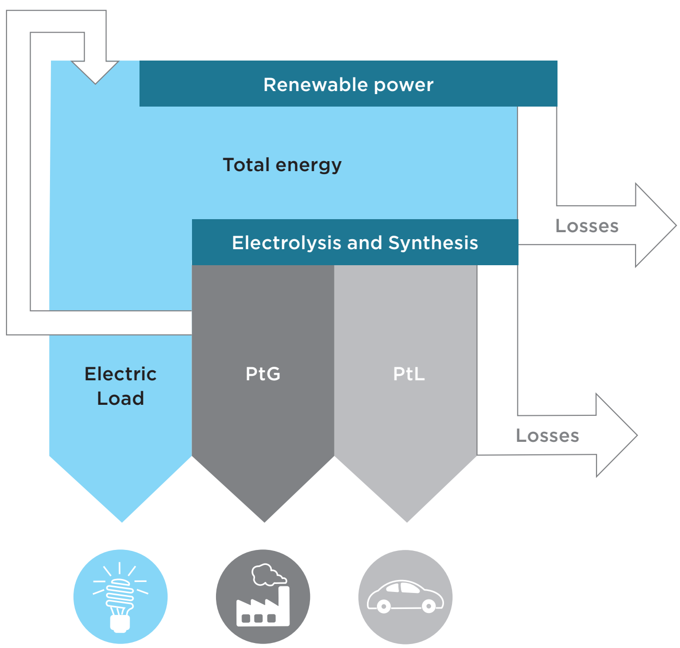

Figure 1: Final energy carrier mix in a RES/renewable fuels scenario with extensive use of electrolysis and SOECs in particular (adapted from an original illustration from the German Federal Environment Agency).

What are sustainable synthetic fuels?

Sustainable synthetic fuels are liquid or gaseous energy carriers that are produced using renewable inputs instead of fossil feedstocks. They are hydrocarbon compounds that share the same chemical composition as conventional fuels like gasoline, and as such represent convenient substitutes to oil, coal, natural gas and all their derived products. Recent technological developments have demonstrated the possibility of combining green power and waste carbon (biomass or recycled CO_2) to synthetize fuels like methanol (CH_3OH), dimethyl ether (DME) or synthetic methane. These could be used to replace their fossil-derived counterparts in the transport sector, the chemical industry, and for electricity and heating generation, resulting in greatly reduced greenhouse gas (GHG) emissions and decreased reliance on declining fossil reserves.

From this perspective, methanol in particular is a very promising fuel: the concept of a "Methanol Economy®"[1] developed by Nobel Laureate George A. Olah illustrates how the use of renewable methanol as the main energy carrier could help address both the demand for liquid energy carriers and the need to reduce GHG emissions.

How could sustainable fuels help reduce CO_2 emissions?

The production of sustainable fuels requires a carbon input, which can be obtained from biomass or recycled CO_2, thereby utilizing something that would have otherwise been undervalued or discarded. The combustion of synthetic fuels, for instance to power a car engine, releases CO_2 into the atmosphere, but this is offset by the fact that an equivalent amount of CO_2 is used in the fuel production process, resulting in an overall reduction in CO_2 emissions.

This CO_2 can be captured from large point emitters like fossil-burning power plants, and in the future from the air itself. This approach builds upon the growing technological expertise on carbon capture, while avoiding the difficulties, costs and risks of CO_2 storage faced by Carbon Capture and Sequestration (CCS) schemes. In this context, the economic value of CO_2 will be dramatically increased, transforming it from an economic and environmental liability to a future energy carrier. Air capture is particularly relevant, as it has the potential to mitigate atmospheric GHG concentrations.

The fuel synthesis process can be powered by renewable energy. Indeed, the technologies for the production of these fuels require energy in the form of electricity and/or heat, which could be supplied by renewable energy sources (RES) like wind and solar. With both renewable power and CO_2 recycling, the whole fuel cycle becomes potentially carbon neutral.

In this scenario, synthetic fuels also represent a way of storing surplus power from RES in the more convenient form of a liquid or gas. These "power-to-liquid" and "power-to-gas" schemes would help buffer the natural intermittency of RES and therefore alleviate one of the major constraints to their large-scale deployment.

In a recent report, the German Federal Environment Agency (UBA)[2] combines all these elements to devise a 2050 scenario where fossil fuels are unnecessary and renewable power is used to produce synthetic fuels for transport, industry, heating etc. (Fig. 1). The UBA estimates that this scenario is technically feasible, and that it would achieve a 95% reduction in GHG emissions from the energy sector.

What are the advantages in comparison to the alternatives?

Synthetic fuels could be directly integrated into existing fuel infrastructures, like filling stations for instance, without incurring excessive costs, technical barriers or behavioural changes. This constitutes a more practical approach compared to other 'green' alternatives, particularly the "Hydrogen Economy". Indeed, while the use of hydrogen (H_2) as a final energy carrier is interesting because of its clean combustion, in practice the storage, transport and distribution of H_2 raises many technological and safety concerns, and the cost of transforming the whole energy infrastructure is likely to prove economically prohibitive. Similarly, massively converting the transport sector to electric vehicles would be a daunting task.

In comparison, replacing fossil-derived petrol and diesel with methanol and DME in the transport sector would only require minimal modifications to account for these fuels' corrosiveness to certain materials (e.g. aluminium and zinc). The incremental cost to provide flexible fuel capability to a new car has been estimated to be as low as € 100.[3]

Other advantages of methanol (and DME) as fuel for conventional internal combustion engines (ICE) include:

- **Safety and engine performance** – Many of the inherent proprieties of methanol, such as its octane rating (~ 100), heat of vaporization and flame speed, translate into enhanced engine performance. In terms of safety, the lower volatility of methanol will result in fewer fuel-related fires. However, methanol (and DME) has only half the volumetric energy density of petrol.

- **Cleaner combustion** – Compared to petrol, combustion of methanol in current ICE produces lower emissions of CO_2 and of other harmful pollutants (e.g. volatile organic compounds and carcinogens). Some power train and marine companies, for example, have shown growing interest in these fuels in order to curb SO_x and NO_x emissions.

While transportation would be the main sector of application, synthetic fuels could also replace fossil-derived products in other sectors:

- **Chemical industry** – Higher-rated (cetane and octane) fuels can also be synthetically produced, while methanol is a flexible C_1 platform chemical that can be transformed into a variety of commercially relevant compounds like propylene, often using already established processes.

- **Electricity generation** – Methanol and synthetic methane can be used in conventional power plants to generate electricity. Moreover, methanol can be used as a fuel in highly efficient electrochemical cells for electricity generation (termed Direct Methanol Fuel Cells). These cells operate at low temperatures, making them potentially ideal for mobile electronic devices and, ultimately, even as a replacement for comparatively inefficient ICE vehicles.

Therefore, with the appropriate mix of renewable fuels, it would be possible to cover all the energy needs of a modern economy.

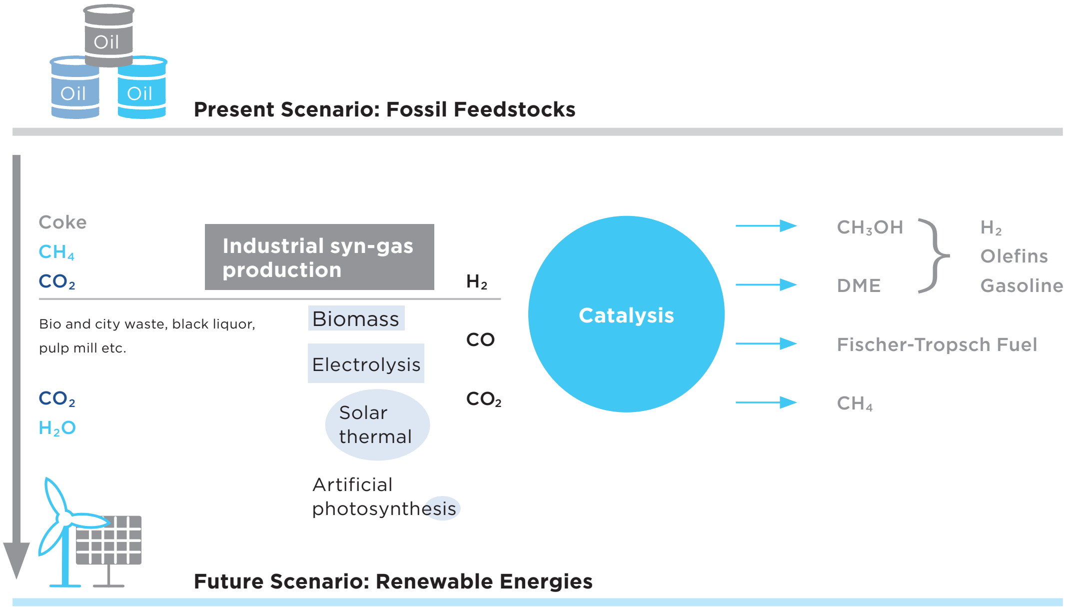

Figure 2: Transition from a fossil fuel-based to a renewable energy-based supply of synthetic fuels coupled with renewable electricity storage.

Technologies for the production of sustainable fuels: state of research

Currently, some synthetic fuels, and especially methanol, are already being produced on an industrial scale, but based on methods that rely on fossil feedstocks (natural gas and coal) and which, in the case of coal, release large quantities of CO_2 during the process.

Conversely, in anticipation of a growing demand for synthetic fuels, a number of innovative, sustainable technologies have emerged and are presently at different stages of industrial maturity.

Electrolysis

Electrolysis is an electrochemical process utilising a direct current to drive an otherwise non-spontaneous reaction. Electricity can be converted into chemical energy very efficiently in an "electrolysis cell". The recent market introduction of Solid Oxide Electrolysis Cells (SOECs) is of particular significance. These high-temperature cells can electrochemically reduce H_2O or H_2O and CO_2 (co-electrolysis) at very high efficiencies to produce either hydrogen or syngas for fuel synthesis. The SOEC typically operates in the 700–1000 °C range, meaning that part of the energy required for the chemical reduction can be obtained from heat as a consequence of internal cell resistance or heat exchange from associated processes. For the process to be carbon neutral, the required electricity should come from a renewable source. After extensive R&D efforts, SOECs are now entering the market and are receiving serious consideration in synthetic fuel production schemes, with recent reports indicating final efficiency of around 70%, depending on the fuel route.[4]

These cells can operate in either electrolysis mode (converting surplus electricity to chemical energy) or fuel cell mode (converting chemical to electrical energy) by changing the current direction. In such a reversible scenario, possible at final efficiencies of ~ 50%, the cell will act to buffer the intermittency of RES. Furthermore, the H_2 and O_2 are physically separated within the cell and are of extremely high purity, reducing the need for purification steps. As a consequence of these points, electrolysis and specifically solid oxide cells represent an efficient and flexible way of converting renewable energy and CO_2 into a synthetic fuel, and will therefore play a central role in future sustainable fuel scenarios.

Valorisation of biomass and associated wastes

The syn-gas required for methanol (and DME) production can also be generated via the gasification of biomass and associated low-value wastes. Various small- to medium-sized enterprises (SMEs) are exploiting this approach to produce synthetic fuels cost-effectively. Precursors include lignocellulosic crops (e.g. sugarcane bagasse), municipal solid waste, paper mill wastes (i.e. black liquor lignosulfonates) and biodiesel by-products like glycerol. The main drawback relates to limitations on biomass availability (quantity, location and food market competition) and additional purification steps, which make large-scale production from biomass sources geographically and economically localised.

Solar thermal

Several labs and research centres are exploring the use of concentrated solar power to thermochemically reduce CO_2 and H_2O to syn-gas. Solar thermochemical approaches operate at high temperatures (> 600 °C), and provide an attractive path to solar fuel production with high-energy conversion efficiencies that do not require rare and expensive metal catalysts. However, this technology has yet to enter the market, with a number of programmes currently going through a reactor prototyping phase.

Artificial photosynthesis

This approach aims to mimic photobiological processes to convert H_2O or H_2O/CO_2 to energy storage compounds ($C_xH_yO_x$) using sunlight and appropriately designed catalysts. To achieve this, typically a solar light-harvesting component using semiconductors is coupled to a suitable redox catalyst to drive the energetically uphill redox reactions. Of all the synthetic fuels production technologies, artificial photosynthesis perhaps shows the greatest long-term potential, but is still far from the market place.

OUTLOOK

Sustainable fuels scenarios like the one laid out by the German Federal Environment Agency represent long-term goals that rely on several technologies reaching industrial maturity in the coming decades. However, some of those technologies are already available, such as SOEC and biomass-based processes. Moreover, the established production methods (those based on fossil feedstock) and industrial infrastructure could be employed to further the market penetration of synthetic fuels, thus paving the way for a gradual switch to more sustainable processes (Fig. 2).

The likelihood and feasibility of this increased market uptake depend on a number of socio-economic and political factors; in particular, private sector initiative alone would not be sufficient, due to the competitiveness of fossil hydrocarbons and general industrial inertia. At least in the short term, further statutory instruments or financial incentives (e.g. tax breaks, subsidies, feed-in-tariff equivalents etc.) must be introduced to support the utilisation of synthetic fuels and promote sustainable-feedstock-based processes.

Earth, Energy and Environment

The Earth, Energy and Environment (E^3) cluster, led by Prof. Carlo Rubbia, aims to identify and evaluate new technological solutions to meet the energy challenges of the future. Key aspects of this endeavour include improving the reliability of renewable energy sources, developing more efficient electric-power transmission technologies and implementing low-carbon uses of fossil fuels. The research activities follow an interdisciplinary approach to energy research, development and support for industrial innovation.

[1] *G. A. Olah, A. Goeppert, G. K. Surya Prakash,* Beyond Oil and Gas: The Methanol Economy, Wiley-VCH, 2009.

[2] Germany 2050 – A Greenhouse Gas-Neutral Country, *German Federal Environment Agency,* October 2013.

[3] *L. Bromberg, W. K. Cheng,* Methanol as an alternative transportation fuel in the US: Options for sustainable and/or energy-secure transportation, *Massachusetts Institute of Technology,* November 2010.

[4] *C. Graves, S. D. Ebbesen, M. Mogensen, K. S. Lackner,* Sustainable hydrocarbon fuels by recycling CO_2 and H_2O with renewable or nuclear energy, *Renewable and Sustainable Energy Reviews,* Elsevier, vol. 15(1), pages 1–23, January 2011.

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Founded in 2009, the IASS is an international, interdisciplinary hybrid between a research institute and a think tank, located in Potsdam, Germany. The publicly funded institute promotes research and dialogue between science, politics, and society on developing pathways to global sustainability. The IASS focuses on topics such as sustainability governance and economics, new technologies for energy production and resource utilisation, and Earth system challenges like climate change, air pollution, and soil management.

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